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Paul Baker
U.S. Army ARDEC
Picatinny Arsenal, NJ

Anthony V. Funari
Hughes Aircraft Co. Missile Systems Group
Canoga Park, CA

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Personal Author: Baker, P.; Funari, A.V.

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ARMY LIGHTWEIGHT EXO-ATMOSPHERIC PROJECTILE

(LEAP)

Paul K. Baker
U.S. Army Armaments Research, Development and Engineering Center
Picatinny Arsenal, NJ

A.V. Funari
Hughes Aircraft Co. Missile Systems Group
Canoga Park, CA

Abstract

This paper will discuss the progress of the Army Lightweight Exo-Atmospheric Projectile (LEAP) Program in the development and demonstration of light weight technologies for kinetic energy kill vehicles. The Army LEAP program is demonstrating these advanced technologies by integrating them into the smallest and lightest interceptor technology demonstrator being developed for the Strategic Defense Initiative Organization. The LEAP design and the results of the final two tests in the ground test program, a full up strapdown test and a free flight hover test, will be discussed as well as future design enhancements and test plans.

I. Introduction

The Gulf War demonstrated for the first time the ability of an interceptor system to successfully intercept incoming ballistic threats. As the threat becomes more sophisticated, the capabilities of the interceptors must grow without a significant increase in cost. One of the drivers in the costs of the system is the size and weight of the interceptor and its components. With smaller, lighter systems, the logistics and support needed will be greatly reduced while transportability and mobility will be increased. The goal of the Strategic Defense Initiative Organization (SDIO) Lightweight Exo-Atmospheric Projectile (LEAP) program has been the development and demonstration of advanced technologies for light weight, kinetic energy interceptors that will fit the needs described above. LEAP has been able to significantly reduce the weight of interceptor component technologies and integrate them into very light, high performance interceptor technology demonstrators. The Army version, shown in Figure 1, is the smallest and lightest of the LEAP vehicles being developed. The interceptor is only 15 cm (6 in) in diameter by 36 cm (14 in) in length and weighs 6 kg (13 lb) in the test configuration. The program recently completed a major milestone by demonstrating operation of a fully integrated vehicle in a ground test environment. This testing, including a live strapdown test and a free flight hover test, was accomplished with 100% success. All subsystems performed much better than required. These tests demonstrated the ability of the LEAP body fixed seeker and guidance systems to control vehicle operation in the presence of propulsion system thruster activity with no degradation in overall performance.

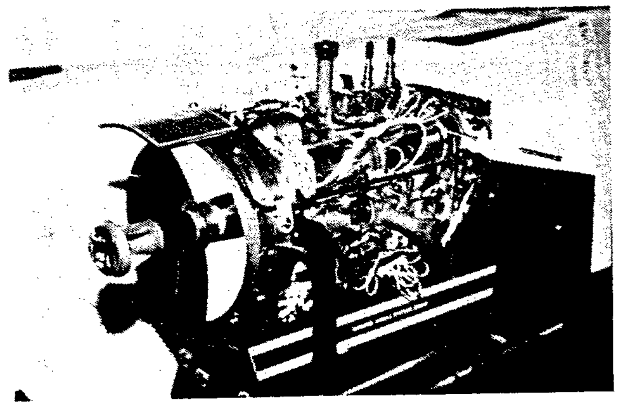

Figure 1 - Lightweight Exo-Atmospheric Projectile (LEAP)

The Army LEAP program is managed for the SDIO by the U.S. Army Strategic Defense Command in Huntsville, AL and is executed and technically administered by the U.S. Army Armaments Research, Development and Engineering Center, Dover, NJ. The prime contractor is Hughes Aircraft Company Missile Systems Group in Canoga Park, CA.

II. Interceptor Overview

The Army LEAP interceptor is an integrated combination of the latest in seeker, propulsion and electronics technologies. The guidance unit, located at the front of the interceptor, consists of the strapdown seeker and flight electronics. The imaging infrared seeker has beryllium primary and secondary reflective optics with a 128 x 128 pixel Mercury Cadmium Telluride (HgCdTe) focal plane array (FPA) housed in a light weight dewar. The electronics unit, located directly behind the primary mirror, is a 14 cm (5.5 in) electronics card formed by mounting eight wafer scale daughterboards on both sides of a single motherboard. The daughterboards each perform a specific function and help off load the central processor. This architecture allows the use of a standard Intel 80386 processor with 4.2 MIPs throughput giving the interceptor added flexibility by being programmable for a variety of targets. The integrated guidance unit weighs in at only 864 gr (1.9 lb).

The propulsion system, developed by The Marquardt Company, is a liquid hypergolic system using hydrazine fuel and nitrogen tetroxide oxidizer. Four 160 Newton (36 lb) divert engines located at the center of gravity (CG) of the interceptor provide lateral maneuver capability to intercept the target. Attitude control is provided by eight 4.5 Newton (1 lb) warm gas thrusters located on the aft bulkhead of the interceptor. The warm gas for attitude control thrust is developed by diverting some of the fuel through a catalyst bed in a warm gas generator located on the front bulkhead. Three small gas bottles on the front bulkhead hold 14,000 psi of helium to pressurize the propulsion system. Total divert capability of the interceptor is greater than 500 meters/second (1640 ft/sec) in the test configuration.

Located on the aft bulkhead are the other elements of the LEAP avionics including the thermal battery, inertial measurement unit, the 11.2 Mbit/second fiber optic telemetry transceiver, and the range safety flight termination system.

III. Ground Test Program

The ground test program was developed to validate the advanced technologies being integrated into the interceptor before the space flight testing was attempted. The program was structured to demonstrate each technology at the component, subsystem, and finally, the integrated interceptor level. The subsystem and system testing were completed with all performing better than predicted. The next step was the integration of complete interceptors for full up testing. Three interceptors have been integrated to date. The first interceptor, configured for ground test operations, successfully demonstrated the performance of the LEAP concept in a fully operational strapdown test and a free flight hover test at the SDIO National Hover Test Facility. Descriptions of the tests and the results are summarized below.

Two more interceptors in a Space Test Projectile (STP) configuration have recently been completed. These projectiles will be used to further validate the LEAP advanced technologies by demonstrating the interceptor performance in a space environment against realistic targets. Three additional interceptors are currently in fabrication for a total of six flight units including one ground test projectile and five space test projectiles.

Strapdown Test

Both the strapdown and free flight hover tests were conducted at the National Hover Test Facility at Edwards Air Force Base, CA. The strapdown test was the first integrated system firing of a fully integrated and functional LEAP and served as a dry run for the hover test count down and procedures. For the first time, all systems in the interceptor operated while exposed to the thermal, vibrational, and electrical interactions from the other systems. The primary area of interest during this test was the interaction between the guidance unit and the propulsion system. Priority was placed on the instrumentation and the data collection at that interface. Figure 2 shows the instrumented projectile mounted in the static test support fixture during the strapdown system test.

The strapdown test was a safety prerequisite for the hover flight but also served as a major check of the procedures and count down to be used during the hover and upcoming flight tests. In the 10 second test, the LEAP fired a programmed series of divert and attitude control pulses predetermined from simulations. The interceptor was entirely self contained; no commands were uplinked from the ground during the test. The LEAP was shock mounted in a fixture which allowed free structural dynamics to occur but allowed no significant lateral motion and limited rotational motion. The interceptor was fully active during the test and tracked a target located 110 meters downrange (the same one used in the subsequent hover test) and calculated navigational parameters on board, such as position and attitude. A complete telemetry data stream, which included full frame IR sensor video on every seeker data frame, was transmitted from the interceptor to a ground receiving station. External instrumentation was added to measure critical temperatures, pressures, currents, voltages, and structural accelerations. The strapdown test provided more pure engineering data than the hover test due to the addition of this instrumentation. This data proved invaluable for assessment of the integrated system performance prior to commiting the projectile to the free flight hover test.

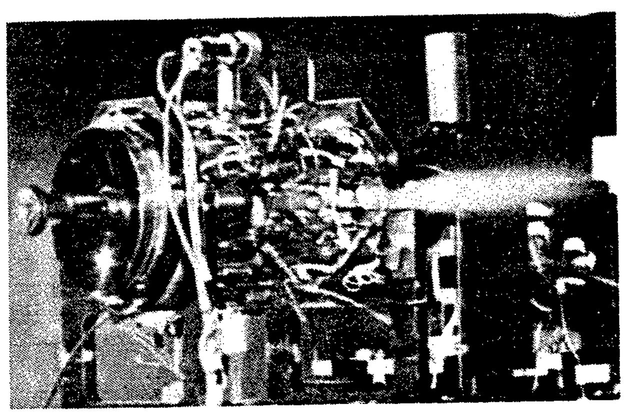

Figure 2 - Instrumented LEAP during strapdown test

Propulsion thrust levels of the integrated system were a critical parameter to be measured during the strapdown test. Due to the small size of the divert and ACS engines it was impossible to directly measure the chamber pressure for thrust level determination. Therefore, the top divert thruster and one attitude control engine were removed during the test and replaced with pressure transducers. This allowed real time measurement of the pressures in the fuel, oxidizer and attitude control system manifolds. The thrust levels were calculated from these pressures based on historical test data from previous thruster component firings.

The downward divert engine was fired on a 5 Hz duty cycle to simulate the required firings to resist gravity

during the hover test. With additional firings of the two lateral thrusters, the divert engines were fired a total of 100 times during the test with no pulse to pulse degradation. The attitude control engines were fired 1400 times with no significant warm gas supply pressure variations. The seeker acquired the target and maintained lock throughout the test. Table 1 summarizes the major system parameters that were monitored and compares the results to the requirement.

The interceptor performance, measured against the test requirements below, indicates the strapdown test was a complete success. All test parameters critical to the success of the interceptor in future applications met or exceeded requirement limits. The test data obtained from the strapdown was used to update the LEAP simulation and to calculate expected hover test trajectory and performance. As a result, confidence that the hover test would be successful was very high.

TOPIC	REQUIRED	MEASURED
Passive CG Control	< 2.0 mm	< 0.2 mm
Divert Thrust Levels	143 ± 14 N	143 ± 14 N
Pressure Control Accuracy	1200 - 1280 psi	1200 - 1280 psi
Electronics Unit Temp	≤ 90° C	84° C
Tracker Performance	≥ 95% Valid Track Gates	100% Valid Track Gates
IMU Noise	< 0.2 deg/sec	< 0.1 deg/sec
Structural Dynamics	< 3 GRMS	2.8 GRMS
Structural Bending Frequency	1500 Hz	1500 Hz

Table 1 - Strapdown Test Data Summary

Free Flight Hover Test

The hover test was the next logical step in the validation progression and was the first free flight of the Army LEAP interceptor. During the hover test, the same test setup was used as during the strapdown. This time, however, the LEAP was free to lift off the platform and hover in free flight. The hover test implemented a lock on before launch of the target used during the strapdown. In the 7 second test, the LEAP acquired the target, fired its bottom divert engine to gain an altitude of 3 meters above the launch cradle, and then maintained that altitude for the remainder of the test. At the end of the test, the LEAP shut down the propulsion system, fell into a safety net, and vented the helium pressurization gas to safe the vehicle for recovery. Throughout the test, the LEAP tracked the remotely located target while firing its divert engines to maintain an "intercept" course. Telemetry data was relayed to the ground receiving station through the slender fiber optic cable seen trailing the projectile in Figure 3 below. The protective cage was added to the interceptor structure to protect the sensitive optics and propulsion system components from damage at the end of the test allowing cost effective reuse of the interceptor for future hover tests.

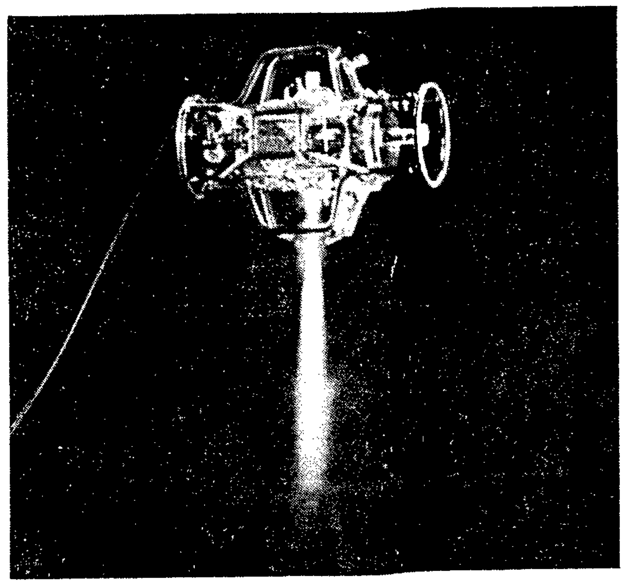

Figure 3 - Army LEAP in free flight during hover test

The fundamental objective of the hover test was to demonstrate the overall controllability of the LEAP while subjected to the harsh propulsion system environment in free flight. The method chosen for implementing attitude control on the interceptor was a major factor in the very light weight system that was achieved. The attitude control engines are very small with a very fast response time (< 1 msec) to maintain stable target pointing within the seeker field of view during flight. While this allows for a very light weight system, the small thrust level and short moment arm do not allow much margin for center of gravity (CG) shift as the propellants are consumed during flight. The divert engines are very large compared to the attitude control engines and therefore could have a devastating effect on interceptor control if they impose too high a disturbance torque on the system when fired. This impact is minimized by locating the center of gravity of the interceptor in the divert engine plane and maintaining it there.

Two methods have been developed to maintain the location of the CG within the specified ± 2 mm requirement. The primary method involving passive CG motion control was employed during the hover test. The fuel and oxidizer tanks in the projectile are paired and located 180° apart. Each pair is drained from opposite ends by driving movable pistons inside the tanks in opposing

directions to expel the liquid propellant. The CG is maintained at the center point as long as the expulsion rates from the opposing tank pairs are equal. During propulsion integration testing, tank expulsion rates were tuned and the resulting matched pairs used for the fuel and oxidizer tanks. This method was verified during the strapdown test by measuring the CG of the interceptor both after the test. The CG location during that test only changed by 0.2 mm from the pretest measurement using only 10% of the allowed 2 mm range.

The second method developed for CG control is an active CG estimator and controller. In this method, CG location is estimated by the interceptor by monitoring the inertial measurement unit (IMU) outputs during divert thruster firings. If the CG excursion exceeds a set boundary, CG control valves on the propellant tanks are opened or closed accordingly to drain the proper tank(s) and move the CG back to the divert plane. During the hover test, the estimator software was operating for verification, but the controller was not implemented.

The onboard center of mass (CM) estimator calculated that the CG did not migrate more than 0.4 mm in any direction during flight, and was less than 0.3 mm from the divert plane for most of the hover flight. These estimates were verified by CG location measurements taken before and after the hover test. The minimal CG movement is also reflected in the performance of the attitude control system during the test. The target migrated an average of only ± 4 pixels in the seeker field of view during the test and body rates were held to ± 3 degrees per second. This is significantly lower than the ± 20 pixels and ± 8.6 degrees per second requirements.

TOPIC	REQUIRED	MEASURED
Attitude Control	± 0.17 °	± 0.03 °
Body Angular Rates	± 8.6 deg/sec	± 3 deg/sec
Terminal Guidance (Miss Distance)	± 2 m	0.2 m
Passive CG Control	< ± 2.0 mm	< 0.2 mm
CG Est Accuracy	± 0.5 mm	± 0.5 mm
Divert Thrust Levels	143 ± 14 N	143 ± 14 N
Pressure Control Accuracy	1200 -1280 psi	1200 -1280 psi
Electronics Unit Temp	≤ 100 ° C	81° C
Tracker Performance	≥ 95% valid Track Gates	100% Valid Track Gates
Seeker Noise	≤ 10 counts RMS	≤ 6 counts RMS

Table 2 - Hover Test Data Summary

The data collected during flight and subsequently evaluated confirms the LEAP hover flight performance as a complete success. The LEAP performed as expected with no anomalies. Table 2 lists the major areas validated during the test.

The data obtained from the hover test has now been used to further update the interceptor simulation allowing more accurate performance predictions for the upcoming space flight tests. The results show that performance required during space testing is well within the demonstrated performance of the Army LEAP.

IV. Flight Test Program

The flight test program is a continuation of the validation of the LEAP technologies. Four flight tests are currently being planned with the Army LEAP interceptor. During the flight test program, closing velocities will be increased from test to test to attain progressively more realistic closing scenarios against cold body targets. In this way, the performance of the LEAP technologies can be demonstrated in a near operational environment. The flight test program will begin with two flights at White Sands Missile Range (WSMR). Two later flights, whose increased closing velocities and the complex trajectories cannot be safely flown at WSMR, will be conducted at the U.S. Army Kwajalein Atoll (USAKA) facility.

In the first WSMR flight, the entire experiment package, consisting of the LEAP interceptor, a target, and a support module called the Payload Module Bus (PMB), is carried aloft by a single booster. The entire experiment is performed exo-atmospheric after separation from the burned out booster. The target is released from the PMB and with separation boost provided by a cold gas thruster. When the thruster is exhausted, the target reorients itself to point back toward the PMB/LEAP. Several hundred seconds pass while the target/PMB separation grows to approximately 20 kilometers. The target then fires a solid axial thruster to boost itself back towards an intercept point 600 meters to the side of the PMB trajectory with a relative closing velocity of 840 m/sec (nominal). At approximately 17 kilometers separation, the LEAP begins acquisition of the target. It is ejected three seconds later, engages its lateral divert thrusters, and maneuvers toward a hit to kill intercept. During this and all subsequent flight tests, all avionics and full seeker video is being transmitted from the interceptor to the ground over a 11.2 Mbit/sec telemetry data link. This allows complete post test reconstruction of the flight and high fidelity evaluation of actual measured flight performance.

In the second WSMR flight, separate boosters will be used to carry the target and experiment module aloft. This will increase the closing velocity at intercept to approximately 2.5 kilometers/second. Acquisition range will be increased to 34 kilometers to allow time for intercept maneuvers after LEAP ejection.

The final two flights currently planned are being performed at USAKA and utilize two boosters as does the latter WSMR flight. These advanced flights, as depicted in figure 4 below, will have further increased relative closing velocities of approximately 5.5 km/sec for the third flight test, with 11 km/sec closing velocity envisioned for the fourth flight.

In order to meet the highly stressing nature of the advanced space flight experiments, design enhancements are being incorporated into the current LEAP interceptor design. A long wave IR seeker system will be substituted for the current medium wave IR system on both USAKA flights. This improvement will allow the interceptors to achieve much greater and more realistic acquisition ranges than on the earlier flights with the current design.

The high closing velocities desired by the SDIO for the fourth test of the series calls for the addition of an axial boost stage on the LEAP. The miniature axial kick stage, supplied by the SDIO, will be controlled by the LEAP interceptor during its flyout. This integrated flight system will help to validate the midcourse interceptor concept. To support the additional flight accuracy needed to accomplish this midcourse mission, the current IMU is being replaced with a fiber optic gyro based IMU from Smiths Industries. In conjunction with the IMU upgrade, the electronics unit is being enhanced with a second data processor to complete the midcourse guidance navigation and control the axial booster. The increased processing capability added by the second data processor will further allow implementation of discrimination algorithms in future flights. As part of the integrated midcourse interceptor system, an RF uplink is being added to receive target state vector updates during midcourse flyout. Guidance algorithms are being added for the midcourse flight and to perform target acquisition after separation of the LEAP interceptor. All previous tests relied on accurate PMB pointing to perform target acquisition prior to STP ejection.

V. Summary

The LEAP program is well on its way to validating advanced technologies for light weight interceptor applications. The successful completion of the strapdown and free flight hover tests demonstrate that the LEAP is ready to enter the flight test phase of the program. The LEAP performance during those tests exceeded all the requirements necessary for successful completion of the flight test series. The validation of the design enhancements being incorporated into the LEAP for the advanced flights will maintain LEAP on the leading edge of technology. These advanced flight test missions will demonstrate the potent lethality of available light weight intercepter technology for hit to kill defense against missile attacks.

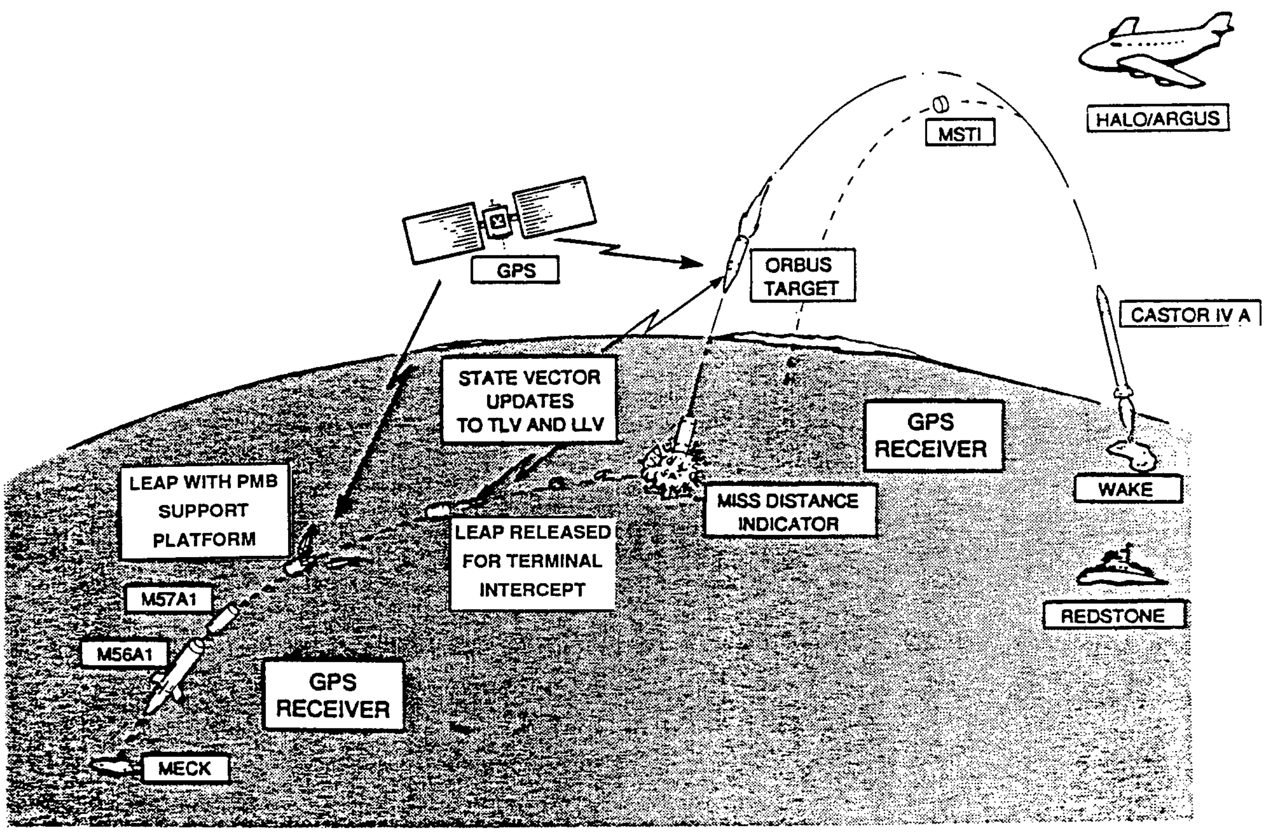

Figure 4 - LEAP advanced space flight test mission overview